DETERMINATION OF ATTERBERG LIMITS USING MOISTURE TENSION METHODS

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BY

A. A. GADALLAH

E.R. RUSSELL

E.J. YODER

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Technical Paper

DETERMINATION OF ATTERBERG LIMITS USING
MOISTURE TENSION METHODS

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

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The Technical Paper attached is offered for approval of publication by the Highway Research Board. The paper "Determination of Atterberg Limits Using Moisture Tension Methods", has been authored by A. A. Gadallah, E. R. Russell, and E. J. Yoder. The paper is a summary of the research and results as reported in JHRP Number 4, 1973, with similar title.

The paper presents the finding of a laboratory investigation of the relationship between Atterburg limits and moisture content as measured by the moisture tension method. The results suggest that the moisture tension test can be used on a routine basis for determining the consistency limits of soils.

The paper is forwarded for approval of publication and as information.

Respectfully submitted,

Harold L. Michael
Associate Director

HLM:mw

cc: W. L. Dolch
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G. D. Gibson
W. H. Goetz
M. J. Gutzwiller
G. K. Hallock
R. H. Harrell
M. L. Hayes
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H. R. J. Walsh
E. J. Yoder

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Technical Paper

DETERMINATION OF ATTERBERG LIMITS USING MOISTURE TENSION METHODS

by

Ahmed Atef Gadallah
Research Assistant

Eugene R. Russell
Instructor in Highway Engineering

and

Eldon J. Yoder
Professor of Highway Engineering

Joint Highway Research Project
Project: C-36-5I
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Purdue University
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December, 1973

DETERMINATION OF ATTERBERG LIMITS USING MOISTURE TENSION METHODS

by

Ahmed Atef Gadallah, Eugene R. Russell, and Eldon J. Yoder

ABSTRACT

This research presents the results of a laboratory investigation of the relationship between the Atterberg limits and the moisture content as obtained by the moisture tension method.

The study was conducted in two basic parts. First, a series of tests was made on 38 soils for the purpose of establishing mathematical models for predicting liquid and plastic limits. The results of these tests showed very good correlation between the standard test results and the moisture-tension test results. The soils used had liquid limit values < 50 percent and plasticity index < 21 percent.

The second part of the study dealt with verifying the mathematical models mentioned above using a total of 144 samples

having a wide range of plasticity values. The results of this series of tests showed good correlation for the liquid limit and fair correlation for the plastic limit.

The results of this investigation indicate that a linear relationship exists between the consistency limits (LL and PL) and the moisture content, WC_i, obtained at various pressure intensities 6, 10, 12 and 18 psi (41.4, 68.9, 82.7 and 124.1 kPa). The results of the study also strongly suggest that the moisture tension test can be used on a routine basis for determining the consistency limits of soils.

INTRODUCTION

The Atterberg Limits have been extensively used for identifying engineering properties of soils and specifying quality of base courses. Almost all specifications for base course materials set some limits on these constants. In order to get consistent test results for the liquid and plastic limits and to minimize the time required for such tests, attempts have been made either to modify the standard method for determination of these limits or to correlate the limits obtained by the standard method with those obtained from a completely different method.

The moisture tension method (10, 14, 15, 16, 18)* has been studied as an alternate procedure for estimating the liquid and plastic limit. The results obtained by this method show a higher degree of reproducibility (10, 15, 16) than the ASTM standard method. The method also permits testing a large number of soil samples simultaneously.

However, there are some limitations relative to the use of the moisture tension method for determining the consistency limits. Previous studies have utilized textural classification of soils as a basis for determining the relationship between moisture tension and liquid limit. Generally, a specific pressure intensity has been recommended for a given soil textural group (14, 15, 16, 18). The use of this technique for the plastic limit determination and for the identification of non-plastic soils had not been fully explored.

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*Numbers in parentheses refer to entries in the List of References.

The primary purpose of this study was to investigate the possibility of using a unique pressure intensity in the moisture tension test for establishing the moisture tension-consistency limits relationship for various soil types regardless of their textural classification, and to specify a limit on the moisture content values, as obtained from the moisture tension method utilizing a unique pressure intensity, below which a soil could be classified as non-plastic.

MATERIALS

This investigation was conducted using thirty-eight soils obtained from the Indiana State Highway Commission. The liquid limit values of these soils ranged from 18 to 50 percent, while the plasticity index values were less than 21 percent.

Four basic soil types were tested as outlined below.

1. Inorganic clays of low to medium plasticity, silty clays, lean clays.
2. Inorganic silts and silt clays.
3. Inorganic clays and silts of low plasticity.
4. Non-plastic materials, mostly silty sands.

MOISTURE TENSION METHOD EQUIPMENT

The apparatus used in this investigation essentially consisted of a commercially available ceramic plate extractor capable of holding three ceramic plates. The ceramic plates used were approximately 10 1/4" (26 cm) in diameter and of a design permitting the tests to be run in the 0 to 1 bar (0 to 100 kPa) pressure range. They are commonly designated as "1 bar ceramic plates" (see Figure 1).

Soil samples are placed in rubber rings 2" (5.08 cm) inner diameter and 1/2" (1.27 cm) high on the ceramic plates which are mounted in the extractor. A maximum of twelve soil samples of this size can be placed on each plate. When the pressure is applied in the extractor, a pressure difference is maintained across each porous plate, the bottoms of which are at atmospheric pressure. Water from the soil is forced out of the extractor through the ceramic plate cells and the outflow tubes until an equilibrium moisture state is reached, and flow then ceases.

TEST PROCEDURES

The liquid and plastic limits were determined in accordance with ASTM designations, D 423-61T and D 424-59 respectively. Four replicated tests were performed on each soil used in this study by one trained operator.

As for the moisture tension test, the general procedure is as follows. Each soil sample of 50 grams weight (consisting of the -#40 sieve fraction) was put into a glass jar. A sufficient amount of distilled water was added and carefully mixed with a spatula until the point where the soil mass could be slowly poured out of the jar. Care was taken that the soil was not so wet as to have free water on the surface when standing. The samples were allowed to stand in the capped jars for two hours before placing them on the plates

The ceramic plates were placed in the extractor and saturated with distilled water prior to placing the soil samples on the plate. Twelve rubber rings of 2" (5.08 cm) inside

diameter and 1/2" (1.27 cm) height were placed on the plate. Each soil sample was placed in the rubber rings on the plate using a spoon. Care was taken to insure that the mixing and preparation process was consistent to minimize the effects of pore sizes and state of packing on the tests results. Although these two factors cannot be precisely controlled by the techniques used in this study, previous studies have shown that good results can be obtained as long as consistency in the method of preparation was maintained (15, 16).

The tubes were next connected and the lid of the extractor closed and tightened with bolts. The end of the outflow tubes were kept constantly under a small amount ± 1" (± 2.5 cm) of water in a beaker to insure outflow into a constant environment as far as humidity was concerned and to check against air leaks (15). Pressure was then applied and adjusted to the required value. The pressure was maintained for 24 hours to insure reaching an equilibrium state. At the close of a run the outflow tube was pinched to prevent possible back flow of water when the pressure in the extractor is released. The pressure was released and the lid of the extractor was opened. The soil samples were transferred to containers and the moisture content of these samples was determined in accordance with ASTM D 2216-63T.

The previously explained method of preparation was selected and used in this research after a preliminary study was conducted to evaluate the effect of method of preparation of soil samples on the moisture tension test results (6). Six soils were

prepared using five different methods of preparation three of which had been utilized and tested in previous research (10, 14, 15). A statistical analysis of the results indicated that; the method of preparation of the soil samples had no significant effect on the moisture tension test results (at $\alpha = 0.05$). This conclusion, however, should be viewed with some caution as the test results apply only to the relatively limited inference space constituted by the soil test samples and methods of preparation that were used. Also, the statistical anlaysis indicated significant interaction between the method of preparation and soil type. This suggests that for some soil types the method of preparation may have an effect on the test results and further indicates that a standardized method of preparation of soil samples is important.

The authors believe that consistency in the method of mixing and preparing the soil samples is of essential value in minimizing changes in the pore sizes and packing state of the soil samples which would affect the moisture tension test results, at least to the extent that such changes do not affect its "reproducibility".

RESULTS

Prediction of Liquid and Plastic Limits of Soils

Previous studies (15, 16) suggested that the region between the upper and lower flex points in the moisture tension curves could represent the plasticity index of the soil, and that this hypothesis is consistent with the mechanism of plasticity as set

forth by Grim (7). Furthermore, the interpretation of two pressure intensities, 3 psi (20.7 kPa) and 20 psi (137.9 kPa) relative to the moisture tension curves obtained in a study by Nishio (10) approximately correspond to the two flexes.

To determine the Atterberg limits-moisture tension relationships, four pressure intensities 6, 10, 12 and 18 psi (41.4, 68.9, 82.7 and 124.1 kPa) were used. These pressure intensities lie in the range 3-20 psi (20.7-137.9 kPa) in which the soil samples exhibit plastic behavior, as suggested in previous studies (10, 15, 16).

For each pressure intensity and using the previously described moisture tension test procedure, the moisture content of each soil was determined. For each of the pressure intensities, four replications were made.

Linear regression models were hypothesized to study the relationships between the measured variables, liquid limit and plastic limit and independent variable, WC_i (the symbol WC_i will be used to represent the moisture content obtained under "i" psi pressure intensity). A separate model was evaluated for each of four pressure intensities. Non-plastic soils were excluded from this part of the study

The data for the regression analysis were handled by two different statistical procedures. The first is commonly referred to as "random combination" and the other as "average values".

In the "random combination" scheme, liquid limit values from the four replications run on each soil by the standard method were randomly combined with the four moisture content values obtained at a corresponding pressure intensity to form a set of four readings. The data obtained for the 28 soil samples were tested for homogeneity of variance. The assumption of homogeneity of variance for both LL and PL test data was accepted and there was no need of transforming the dependent variables. The process was repeated for the plastic limit data.

In the "average values" scheme, the mean value of the four replicates of the standard liquid and plastic limit tests for each soil was used as the dependent variable. Similarly, the mean WC_i value for each soil was used as the independent variable. Using these average values in the regression analysis eliminates a part of the variation among the replicate measurements, which may make the coefficient of determination R^2 misleadingly high. However, this study indicated that there is very little difference in R^2 due to the use of the two schemes (random combination vs. average values). The use of the prediction models obtained by utilizing the random combination scheme could better represent the inference space for this study.

Interpretation of the Regression Analysis Results

The models obtained from the regression analysis of the test data were examined and the ones providing the best fit of the data were selected. The criterion used to evaluate the best regression equation was the coefficient of determination, R^2,

the ratio of the variation explained by the regression equation to the total variation of the data about the mean. Also, the significance of the regression was tested by an F-test at an α level of 0.05. The residuals obtained from the regression analysis were examined to determine if they were correlated. It was observed that the residuals did not show any predominant trend.

The results of the regression analysis using the Random Combination Scheme are summarized in Table 1. An examination of these results indicates that these linear first-order regression models are appropriate for representing the relationship between consistency limits (LL and PL) and the moisture content WC_i. The data show that:

1. The prediction models obtained for both the liquid and plastic limits show a high coefficient of determination, R^2. Also, a linear relationship exists between the liquid or plastic limit and the equilibrium moisture content for each of the pressure intensities utilized in this investigation, namely, 6, 10, 12, and 18 psi (41.4, 68.9, 82.7 and 124.1 kPa).
2. The regression models obtained for the prediction of the liquid limit show a higher R^2 value than that obtained for the prediction of the plastic limit values.

TABLE 1. Prediction Equations for the Liquid and Plastic Limits

PRESSURE	MODEL	R^2	Standard Error	No. of Samples
6 psi (41.4 kPa)	$LL = -3.5863 + 1.3201\ WC_6$	0.93	2.58	112
	$PL = 1.4094 + 0.7097\ WC_6$	0.94	1.22	112
10 psi (68.9 kPa)	$LL = -3.5437 + 1.4867\ WC_{10}$	0.95	2.18	112
	$PL = 1.9906 + 0.7737\ WC_{10}$	0.90	1.59	112
12 psi (82.7 kPa)	$LL = -2.7809 + 1.4892\ WC_{12}$	0.95	2.09	112
	$PL = 2.7699 + 0.7570\ WC_{12}$	0.87	1.85	112
18 psi (124.1 kPa)	$LL = -1.9158 + 1.5029\ WC_{18}$	0.92	2.68	108
	$PL = 3.9766 + 0.7299\ WC_{18}$	0.78	2.41	108

3. For the liquid limit prediction models, the R^2 values remain almost the same (0.92-0.95) with changes in the pressure intensity. Contrarily, for the plastic limit prediction models, the R^2 values decrease directly with the increase in pressure intensity utilized, (the prediction model obtained at 6 psi (41.4 kPa) has an R^2 value of about 0.94, and that at 18 psi (124.1 kPa) has an $R^2 = 0.78$).
4. The deviations of the predicted LL and PL values from the observed values are within the range of those obtained in replicated standard LL and PL test results (6, 9, 10, 15). To make the prediction models less cumbersome and easy to handle, it was decided to simplify the regression coefficients. As the liquid and plastic limit values are generally determined to the nearest whole percent moisture content; rounding off the regression coefficients in the prediction equations will not affect the results appreciably.

Detection of Non-Plastic and Low Plasticity Soils

This aspect of the study is concerned with the identification of non-plastic* soils by the moisture tension method. The moisture contents (WC_i) of the non-plastic soils were obtained by using four different pressure intensities. Study of the moisture content values indicated WC_i values of the non-plastic soils had an approximate upper-bound limit depending upon the

*Non-plastic soils are defined as those, sandy or non-cohesive soils for which it is difficult or impossible to determine the plastic limit.

pressure intensity used. Similarly, for the soils exhibiting a plasticity index (PI) less than 3% as well as those with P.I.'s between 3% and 6%, the moisture content (WC_i) values were within specific ranges. Therefore, it appears that non-plastic and low plasticity soils can be identified by their limiting WC_i values. These limiting values for various pressure intensities are shown in Table 2.

Figure 2 shows the relationship of the liquid and plastic limits with the moisture content values WC_i, at various pressure intensities, (using the simplified regression coefficients). These relationships can be divided into several distinct segments. The lowest segment "A" indicates the non-plastic region, the region "B" signifies the range from non-plastic to a PI < 3% and region "C" approximates the WC_i values for soils exhibiting PI values between 3 and 6 percent. The region beyond "C" is for soils exhibiting a PI greater than 6 percent.

Verification of the Proposed Mathematical Models

To verify the proposed relationships, additional soil samples with previously determined consistency limits were obtained from a highway commission laboratory outside Indiana. A total of 144 samples representing a large range in soil texture were tested. The liquid limits of these samples ranged between 15 and 80 percent; the highest plasticity index was 60 percent. The moisture tension method test was run on these samples at a pressure intensity of 10 psi (68.9 kPa) because a high R^2 value was obtained for both the liquid and plastic limit prediction

TABLE 2. WC_i Ranges for Non-Plastic and Low Plasticity Soils

Pressure	WC_i^* Range for Non-Plastic Soils	WC_i^* Range for Soils with PI < 3%	WC_i^* Range for Soils with (3% < PI < 6%)
6 psi (41.4 kPa)	<10	10-15	15-20
10 psi (68.9 kPa)	< 9	9-14	14-19
12 psi (82.7 kPa)	< 8	8-13	13-18
18 psi (124.1 kPa)	< 7	7-12	12-17

*Values are in percent moisture content.

models for this pressure. Though the models indicate that utilizing a pressure intensity of 6 psi (41.4 kPa) would result in even a higher coefficient of determination R^2, using such a relatively low pressure intensity requires more experimental control and more careful adjustments of the pressure regulators than the higher pressures. The equilibrium moisture content is a function of the pressure intensity applied, i.e., for low pressure, WC_i is higher than that obtained under high pressures. Also it was observed that transferring the soil samples from the ceramic plates to the containers after releasing the pressure was easier at 10 psi (68.9 kPa) pressure intensity.

Liquid Limit Relationships

The liquid limit prediction model,

$$LL = -3.50 + 1.50\ WC_{10} \qquad (1)$$

was applied to the check samples data. The coefficient of determination, R^2, resulting from applying model No. 1 to the check samples data was 0.89.

In order to investigate the possibility of a better fitting model for the check samples, a regression analysis of the check samples data was made. The analysis resulted in the following linear model with a coefficient of determination, $R^2 = 0.92$.

$$LL = -4.38 + 1.45\ WC_{10} \qquad (2)$$

A plot of standard LL values vs. WC_{10} for the check samples together with models (1) and (2) are shown in Figure 3. The deviations of the predicted values from the standard values

using both models No. 1 and 2 are summarized in Table 3.

The next step in this analysis was to statistically compare the original and check sample models. Both models have a general form of the type:

$$LL = b_0 + b_1 \quad WC_{10} \tag{3}$$

It was found that the slope b_1 and the intercept b_0 of the Purdue Sample model lie within the 95% confidence limits for the regression coefficients β_1 and β_0 respectively, of the check sample model. The shift in intercept values could be attributed primarily to operator variability.

These models suggest that a linear model may be the best fit to define the LL vs. WC_{10} relationship for any soil. However, for good correlation one might have to adjust the parameters b_0 and b_1 for soils from different geographic areas.

Plastic Limit Relations

A correlation analysis of PL and WC_{10} for the 144 check samples resulted in a simple correlation coefficient, $r = 0.63$. Because of the apparent low correlation when the results of all 144 samples were used; it was decided to restrict the verification of the PL relationship to just those soils having a PI < 21 percent and an LL < 50 percent. This constitutes the inference space of the model developed earlier in this research (Purdue data) and it also covers the majority of soils that an agency would test under normal circumstances.

TABLE 3. Summary of Deviation of Predicted LL Values from the Standard Values

Deviation*	Purdue Sample Model**		Check Sample Model***	
	No. of Observations	Percent of Observations	No. of Observations	Percent of Observations
1-2	65	45.2%	87	60.5%
3-4	42	29.2%	36	25.0%
> 4	37	25.6%	21	14.5%

* Standard LL minus predicted LL in percent

** Using the model: $LL = -3.50 + 1.50\ WC_{10}$

***Using the model: $LL = -4.38 + 1.45\ WC_{10}$

The data lying inside the prescribed range were included for the analysis (91 data points). The plastic limit prediction model (Purdue Data),

$$PL = 2.0 + 0.75 \quad WC_{10} \qquad (4)$$

the best fitting linear regression model (from check samples),

$$PL = 4.77 + 0.54 \quad WC_{10} \qquad (5)$$

and the reduced data (91 data points) are shown in Figure 4. Model No. 5 resulted in a coefficient of determination $R^2 = 0.60$. The simple correlation coefficient, r, between PL and WC_{10} for the reduced data increased to 0.78.

The deviation of predicted values, using both models 4 and 5 from the standard plastic limits are summarized in Table 4.

Non-Plastic and Low Plasticity Soils

It was observed that the ranges of WC_{10} values postulated for non-plastic and low plasticity soils are valid for the check sample data. These ranges are indicated in Figures 3 and 4.

CONCLUSIONS

The objective of this study was to investigate the feasibility of using the moisture tension method to determine Atterberg limits. The conclusions are as follows:

1. Linear relationships were developed between the consistency limits (LL and PL) and the moisture content, WC_i, obtained at 6, 10, 12 and 18 psi (41.4, 68.9, 82.7 and 124.1 kPa) pressure intensity. These relationships offer the possibility of using

TABLE 4. Summary of Deviation of Predicted PL Values from the Standard Values

Deviation*	Purdue Sample Model**		Check Sample Model***	
	No. of Observations	Percent of Observations	No. of Observations	Percent of Observations
1-2	19	21.0%	57	62.5%
3-4	27	29.5%	29	32.0%
> 4	45	49.5%	5	5.5%

* Standard PL minus predicted PL in percent

** Using the model: $PL = 2.0 + 0.75\ WC_{10}$

***Using the model: $PL = 4.77 + 0.54\ WC_{10}$

linear models, correlating the consistency limits with the moisture content, WC_i, for predicting liquid and plastic limits.

2. The non-plastic and low plasticity soils can be identified by their WC_i values, as obtained by the moisture tension method.

3. The results of the verification of the consistency limits - WC_{10} relationships indicated that: The liquid limit prediction model showed good agreement with the best-fitting linear regression model for the check samples data. A linear relationship for these parameters explains 92% of the variation in the data.

   The plastic limit model resulted in a relatively poor prediction of the plastic limit values of the check samples. The analysis to determine the best-fitting linear model for the check sample data resulted in an R^2 value of 0.60. This low value can possibly be explained by the fact that forces other than capillarity affect the moisture tension test results, especially in the case of clays. Baver (1) suggested that the water holding capacity of soils is a function of the clay content, the type of clay minerals, amount of organic matter and porosity. It is possible that different mineralogical characteristics and origin of the check soils may have caused the differences observed

during the verification of these models. Further, some of the difference can be attributed, to the variability between different operators.

The ranges of WC_{10} values suggested previously for non-plastic soils, as well as those with low plasticity, (based on original data) were verified by the check sample data.

REFERENCES

1. Baver, L. D., "Soil Physics", 3rd Edition, John Wiley and Sons, Inc., New York, 1956.
2. Casagrande, A., "Research on the Atterberg Limits of Soils", Public Roads, October, 1932.
3. Casagrande, A., "Classification and Identification of Soils", Transaction, ASCE, Vol. 113, pp. 901-991, 1948.
4. Dawson, R. F., "Investigations of the Liquid Limit Test on Soils", Symposium on Atterberg Limits, ASTM Special Technical Publication No. 254, pp. 190-195, 1959.
5. Draper, N. R., and Smith, H., "Applied Regression Analysis", John Wiley and Sons, Inc., New York, 1966.
6. Gadallah, A. A., "Determination of Consistency Limits of Soils by Moisture Tension Method", Research Report No. 4 Joint Highway Research Project, Purdue University, February, 1973.
7. Grim, R. E., "Applied Clay Mineralogy", McGraw-Hill Book Company, Inc., New York, 1962.
8. Livneh, M., Kinsky, J., and Zaslavsky, D., "Correlation of Suction Curves with the Plasticity Index of Soils", Journal of Materials, JMLSA, Vol. 5, No. 1, pp. 209-220, March, 1970.
9. Morris, M. D., Ulp, R. B. and Spinna, R. J., "Recommendations for Changes in the Liquid Limit Test", Symposium on Atterberg Limits, ASTM Special Technical Publication No. 254, pp. 203-211, 1959.

10. Nishio, T. K., "An Investigation of the Use of the Moisture Tension Method for Determination of Liquid and Plastic Limit Values of Soil", Research Report No. 15, Joint Highway Research Project, Purdue University, July, 1972.

11. Ostle, B., "Statistics in Research", Iowa State University Press, 1963.

12. Richards, L. A., "Methods of Measuring Soil Moisture Tension", Soil Science No. 68, pp. 95-112, 1949.

13. Richards, L. A., "Porous Plate Apparatus for Measuring Moisture Retention and Transmission by Soil", Soil Science, No. 66, pp. 105-110, 1948.

14. Rollins, R. L., and Davidson, D. T., "The Relation Between Soil Moisture Tension and Consistency Limits of Soils: Methods for Testing Engineering Soils", Iowa Engineering Experiment Station Bulletin No. 192, pp. 210-220, 1960.

15. Russell, E. R., and Mickle, J. L., "A Study to Correlate Soil Consistency Limits with Soil Moisture Tensions", Final Report, Project 490-S, Engineering Research Institute, Iowa State University, Ames, Iowa, 1965.

16. Russell, E. R., and Mickle, J. L., "Liquid Limit Values by Soil Moisture Tension", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM3, pp. 967-989, May 1970.

17. Seed, B. H., Woodward, R. J., and Lundgren, R., "Fundamental Aspects of Atterberg Limits", ASCE, Journal of the Soil Mechanics and Foundations Division, Vol. 90, No. SM6, pp. 75-109, November, 1964.

18. Sultan, H. A., "Relation Between Soil Moisture Tension and the Consistency Limits for Utah Soils", unpublished M.S. Thesis, Library, University of Utah, 1961.

19. Terzaghi, K., and Peck, R. B., "Soil Mechanics in Engineering Practice", John Wiley and Sons, Inc., New York, 1967.

20. Uppal, H. L., A Scientific Explanation of the Plastic Limit of Soils", Journal of Materials, Vol. 1, No. 1, pp. 164-179, March, 1966.

Figure 1. Set Up of Equipment Showing Two Extractors

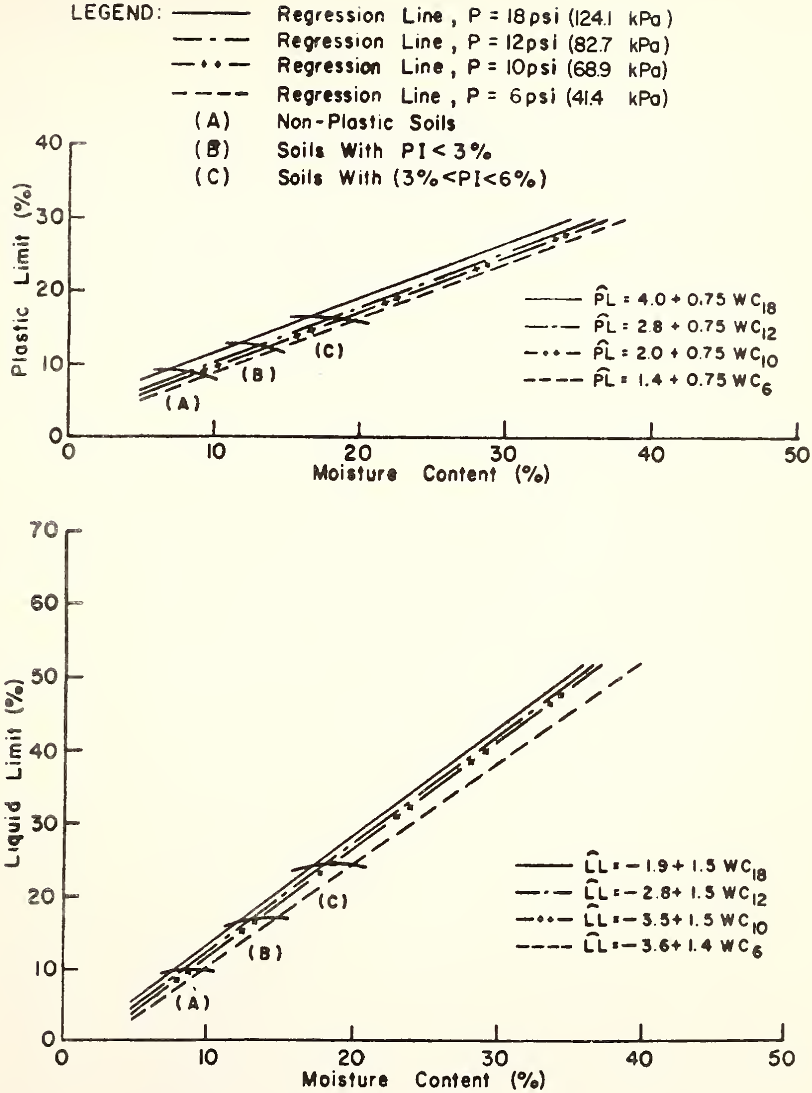

FIGURE 2 Relationship of Liquid and Plastic Limits With The Moisture Content at Various Pressure Intensities

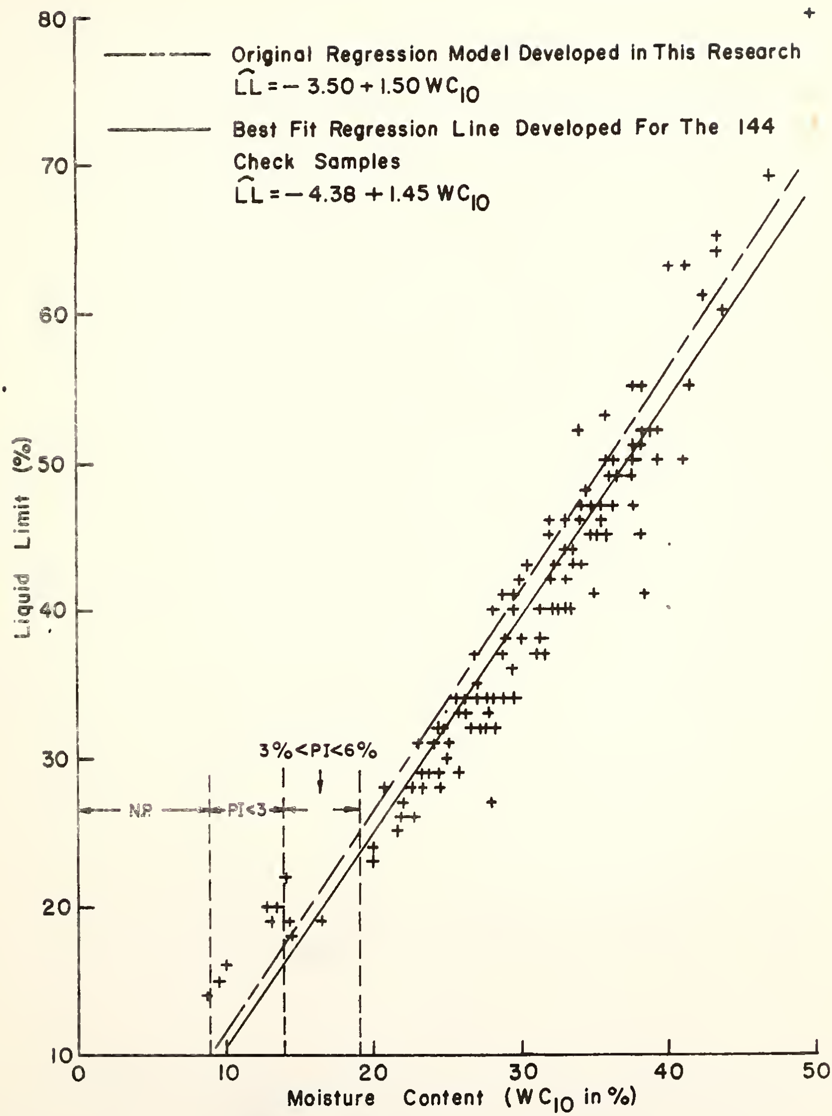

FIGURE 3. Relationship Between The Liquid Limit and Moisture Content at 10psi (68.9 kPa) For The Check Samples (144 data points)

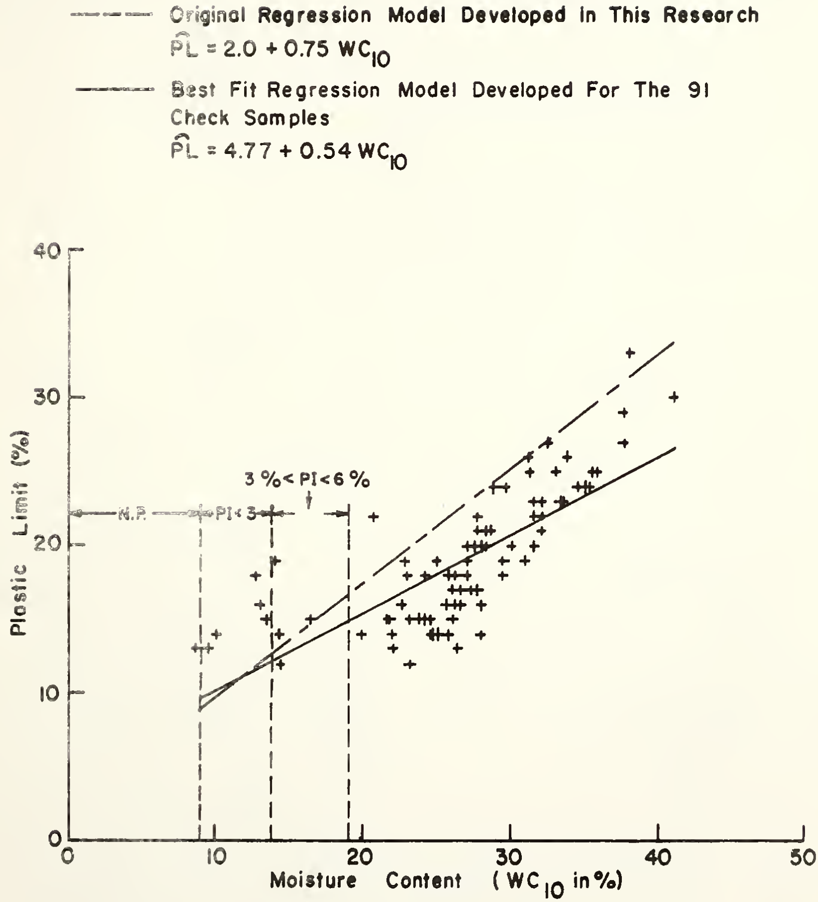

FIGURE 4. Relationship Between The Plastic Limit and Moisture Content at 10 psi (68.9 kPa) For The Check Samples (91 data points)